

LETTER TO THE EDITOR

Direct imaging discovery of 12-14 Jupiter mass object orbiting a young binary system of very low-mass stars.

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ABSTRACT

Context. Though only a handful of extrasolar planets have been discovered via direct imaging, each of these discoveries had tremendous impact on our understanding of planetary formation, stellar formation and cool atmosphere physics.

Aims. Since many of these newly imaged giant planets orbit massive A or even B stars we investigated whether giant planets could be found orbiting low-mass stars at large separations.

Methods. We have been conducting an adaptive optic imaging survey to search for planetary-mass companions of young M dwarfs of the solar neighbourhood, to probe different initial conditions of planetary formation.

Results. We report here the direct imaging discovery of 2MASS J01033563-5515561ABb, a 12-14 M_{Jup} companion at a projected separation of 84 AU from a pair of young late M stars, with which it shares proper motion. We also detected a Keplerian-compatible orbital motion.

Conclusions. This young L-type object at planet/brown dwarf mass boundary is the first ever imaged around a binary system at a separation compatible with formation in a disc.

1. Introduction

The discovery of hundreds of extrasolar planets in the last 20 years has radically modified our understanding of planetary formation. Though radial velocity and transit detection methods have proven by far the most prolific, the few planetary-mass companions which have been discovered by direct imaging have provided very challenging constraints for formations models, especially the core-accretion model (Pollack et al. 1996) that is preferred to explain the formation of Solar System planets. 2M1207B, discovered by Chauvin et al. (2004), with a mass-ratio of 20-25% is too massive with respect to its primary to have formed by core accretion, while most of HR8799 (Marois et al. 2008) would be very difficult to form in situ by core-accretion. Only β -Pictoris b (Lagrange et al. 2010) fits relatively well with the core-accretion scenario. Also, several imaged substellar companions (e.g. Chauvin et al. 2005; Lafrenière et al. 2008; Carson et al. 2012) straddle the arbitrary - and debated- 13 M_{Jup} planet/brown dwarf boundary. For most of these massive planets (or light brown dwarfs) the formation mechanism, stellar or planetar, is still debated (Luhman et al. 2006; Bate 2009; Rafikov 2011; Boss 2011;

Stamatellos et al. 2011).

Circumbinary planets, such as Kepler-16 ABb (Doyle et al. 2011) are even rarer and provide peculiar constraints on planetary formation scenarios, notably on the influence of binarity on planet-forming discs.

We present here the discovery of 2MASS J01033563-5515561ABb, hereafter 2MASS0103(AB)b, a unique a 12-14 M_{Jup} substellar companion to a late M dwarf binary system.

2. A 12-14 M_{Jup} companion orbiting around a young late M binary system

2.1. Observations and data reduction

We imaged 2M0103 in November 2012 (run 090.C-0698(A)), in L' band as one target of our NACO survey for planetary companions to young nearby M dwarfs (Delorme et al. 2012). We used NACO infrared wave-front sensor and observed in pupil tracking (only 12° of rotation) and cube mode in L' , and our follow-up observations in JHK_S on the same night used field tracking. Table 1 shows the details of our observations.

The target star was resolved as a low contrast, 0.25'' binary on these raw images and an additional source was identified at $\sim 1.8''$ at the north west of 2M0103A. In order to measure the proper motion of this source, we retrieved

Send offprint requests to: P. Delorme, e-mail: Philippe.Delorme@obs.ujf-grenoble.fr. Based on observations obtained with NACO on VLT UT-4 at ESO-Paranal (runs 090.C-0698(A) and 70.D-0444(A)).

Table 1. Summary of the NACO (VLT-UT4) observations of 2M0103AB (RA=01:03:35.63; Dec=-55:15:56.1).

UT Date	Filter	Exp. time	Comments
2012-11-25	L'	$32 \times 200 \times 0.2 = 1280s$	Seeing:
	K_S	$8 \times 20 = 160s$	$0.7'' - 0.8''$
	H	$8 \times 20 = 160s$	Airmass:
	J	$4 \times 5 = 20s$	1.16-1.25
2002-10-28	H	$5 \times 10 \times 2 = 100s$	Archive data

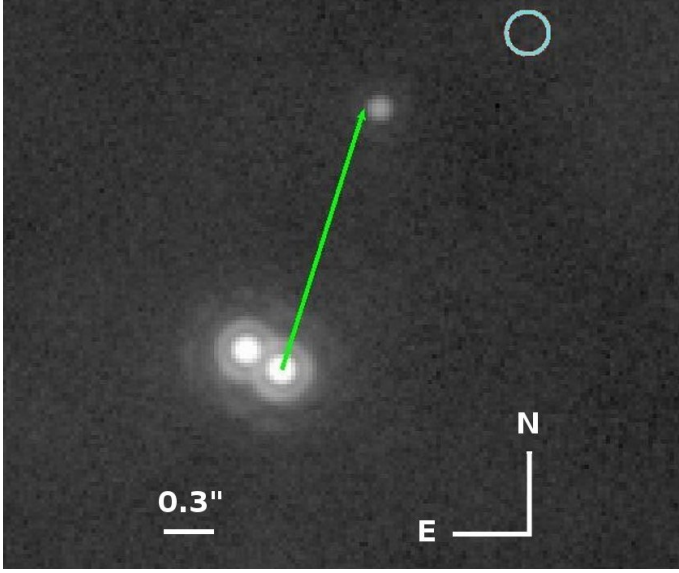


Fig. 1. 2MASS0103(AB)b in November 2012, with NACO in L' band. The green arrow shows the position of the companion in 2012. The light-blue circle identifies the expected position of the companion if it had been a background source.

ESO archive NACO H -band images of 2M0103, obtained in October 2002 (run 70.D-0444(A)). These early images were acquired in field tracking and with poor adaptive optics correction. We stacked the best 50% of the frames, for which the central binary was resolved, totalling 100s exposure time on target.

We used the IPAG-ADI pipeline as described in Delorme et al. (2012) to reduce the frames (bad pixel interpolation, flat, recentring, derotation and stacking). Although both the secondary component and the companion appear clearly after a simple stack of all exposures (see Fig.1), we performed ADI (Marois et al. 2006) and LOCI (Lafrenière et al. 2007) star subtraction procedures to detect eventual other companions. None was detected was detected down to a contrast of ~ 7.5 magnitudes at $0.5''$, resulting in a detection limit of $\sim 2.5 M_{Jup}$ at 25 AU for an age of 30 Myr (see discussion below).

2.2. Host star properties

The primary star 2MASS J01033563-5515561 was identified as part of a survey designed to identify new, later than M5 candidate stars and brown dwarfs to the young, nearby moving groups and associations Beta Pictoris, TW Hydrae,

Tucana-Horologium (THA), Columba, Carina, Argus and AB Doradus (ABDMG) (Torres et al. 2008). The details of this analysis will be presented in Gagn et al. (in prep.), but the principle is to identify promising candidate members to these moving groups using astrometry, proper motion and photometry from a correlation of 2MASS and WISE catalogs, with a modified version of the Bayesian analysis described in Malo et al. (2013). One of the first robust candidates identified in this project is 2MASS J01033563-5515561, which we have followed with GMOS-S at Gemini South to obtain the optical spectra. This spectrum matches a M5.5/M6 spectral-type and shows strong H-alpha emission at 656 nm, with an equivalent width of $10.23 \pm 0.55 \text{ \AA}$. No nearby X-ray source was found in the ROSAT archive (Voges et al. 1999), indicating the target is not a strong X-ray emitter. In parallel to this, we have obtained a trigonometric distance, of 47.2 ± 3.1 pc for this object (A. Riedel, private communication, using the CTIO 0.9m through the CTIOPI program, using 49 R -band images taken on 11 nights between October 26th, 2007 and November 13th, 2012, and reduced using methods from Jao et al. (2005); Riedel et al. (2011). The complete parallax analysis for 2M0103, together with many other objects, will be published in Riedel et al., in preparation. During the NACO runs described earlier, we have also noticed the primary is in fact a binary with a flux ratio of 0.8 in the L' band. Taking into account this binarity and the trigonometric distance, we find Bayesian probabilities of 99.6% and 0.4% for membership to THA and ABDMG respectively. The field hypothesis has a probability of 10^{-14} . 2M0103AB is therefore a strong candidate member of the Tucana-Horologium association, aged ~ 30 Myr (Torres et al. 2008).

We must stress that those probabilities are not absolute ones in the sense that even a sample of candidates with a 100% Bayesian probability will contain a certain number of false-positives. Follow-up observations of robust candidates in Malo et al. (2013) have shown that the false-positive rate is 10% for candidates without parallax in THA. Though the membership analysis in our study is not exactly the same, the risk of a false positive is very low, especially because we do have a parallax measurement, meaning that 2M0103AB is very probably a bona-fide member of THA. We will assume in the following that the 2M0103 system is aged 30 Myr.

According to BT-Settl 2012 isochrones (Allard et al. 2012; Baraffe et al. 2003), and assuming a distance of 47.2 ± 3.1 pc and an age of 30 Myr, 2M0103AB is a low mass binary with masses of $[0.19; 0.17] \pm 0.02 M_{\odot}$ for [A;B] respectively, see table 2. The projected separation between A and B was $0.26 \pm 0.01''$ in 2002 and $0.249 \pm 0.003''$ in 2012. The projected distance was around 12 AU at both epochs, but the position angle changed significantly, from 71.2° in 2002 to 61.0° in 2012.

2.3. Proper motion analysis: a bound companion

During our November 25th, 2012, L' band NACO observations of 2M0103 (run 090.C-0698(A)), we identified a candidate companion with a separation of $1.78''$ and a position angle of 339.3° from the primary 2M0103A. Even if contamination by background objects is relatively low in L' band compared to shorter wavelength (see Delorme et al. 2012),

Table 2. Host system absolute magnitudes compared with BT-Settl isochrones at 30Myr absolute magnitudes (2MASS for JHK and NACO for L').

Filter	M_J	M_H	M_{K_s}	$M_{L'}$
2M0103A	7.36 ± 0.05	6.78 ± 0.05	6.44 ± 0.05	6.04^*
2M0103B	7.56 ± 0.05	6.98 ± 0.05	6.64 ± 0.05	6.24^*
Model $0.2M_{\odot}$	7.31	6.75	6.50	6.1
- $0.175M_{\odot}$	7.51	6.95	6.70	6.3

Notes. * Since no calibrated photometry is available in L' , these magnitudes are derived from the modelled $K_S - L'$.

Table 3. Separation (Sep.) and position angle (PA) of the companion, with respect to 2M0103A and to the center of mass of the binary.

	2002-10-28	2012-11-25
Sep. from 2M0103A($''$)	1.682 ± 0.015	1.784 ± 0.003
PA from 2M0103A($^{\circ}$)	$341.7 \pm 0.05^*$	$339.8 \pm 0.01^*$
Sep. from barycenter($''$)	1.718 ± 0.015	1.770 ± 0.003
PA from barycenter($''$)	$338.0 \pm 0.05^*$	$336.1 \pm 0.01^*$

Notes. * The error in position angle refer to the relative error between both epochs. The absolute error, dominated by systematic uncertainties in the position of the reference stars in theta Ori., is $\pm 0.4^{\circ}$.

the probability that this companion was a contaminant was high. However, the companion was redder in $K_S - L'$ than its late M host system, meaning that the companion is of even later spectral type, considerably decreasing the likelihood of the contaminant hypothesis, but not incontrovertibly proving that the companion is bound. A definite proof of companionship was however provided thanks to archive images taken with NACO on October 28th, 2002. Using this 10 years time base, we could determine that 2MASS0103(AB)b unambiguously (contamination probability $< 0.001\%$, taking into account parallax motion) shares the proper motion of 2M0103AB (see Fig.1) and is therefore a bound companion. The relative astrometry at each epoch is shown on table 3.

2.4. Companion properties

Our current information about the physical properties of the system relies on the J, H, K and L' photometry and astrometry from our November 2012 NACO run, as well as October 2002 NACO archive images. The resulting Moffat-fitting photometry is $J=15.4 \pm 0.3$, $H=14.2 \pm 0.2$, $K_S=13.6 \pm 0.2$ and $L'=12.6 \pm 0.1$. We emphasize that all these measurements were derived relative to 2M0103A, which introduces significant systematic errors (hence the large errors bars). The absolute magnitudes of the companion, for a distance of 47.2 pc, are shown in table 4, and are compatible with 2MASS0103(AB)b being a 12 to 14 M_{Jup} companion orbiting at 84 AU around the young low-mass binary 2M0103AB. Note that 2MASS0103(AB)b very red colours in $JHKs$ do not match the colours of field objects of similar absolute magnitudes and are similar to known, early L-type, young planetary-mass objects, thus independently confirming the youth of the system (see also Fig. 2).

It is to be noted that the age of THA is not perfectly known and the dispersion of the age estimations of individual stars in THA span the 20-50Myr range (Zuckerman & Webb 2000; Torres et al. 2000). If we assume an age of 20 Myr, 2MASS0103(AB)b would be a 12-13 M_{Jup} planet, while it would be a 14-15 M_{Jup} brown dwarf if we assume an age of 50 Myr. In spite of the naming change, the physical differences in mass estimates for the 20 Myr and the 50 Myr hypothesis are much smaller than those derived in Marois et al. (2010) for HR8799bcde planets in the same age range. An explanation is that objects more massive than $\sim 10 M_{Jup}$ undergo some deuterium burning in this age range, somewhat compensating cooling down mechanisms. However, since there is currently no robust independent mass constraint for any imaged exoplanet (saved to some extent for β Pic. b, see Lagrange et al. 2012), it is probable that the systematic uncertainties coming from substellar models inaccuracies are larger than those arising from age uncertainties. For the sake of comparison with other substellar companions found in associations of the same mean age of 30 Myr, we assume in the following that 2MASS0103(AB)b is a 12-14 M_{Jup} object aged 30 Myr.

A possible analog, if confirmed as bound, would be the substellar object located at a projected separation of 1100 AU from the binary system SR12AB (Kuzuhara et al. 2011). The properties of 2MASS0103(AB)b (mass of 12-14 M_{Jup} , age of 30 Myr, colours, projected separation of > 50 AU) and observed colours are also much like AB pic b (K1V Chauvin et al. 2005) or κ Andromeda b (Carson et al. 2012). The properties of the host systems are however quite different. While κ Andromeda is a massive B star ($\sim 2.5M_{\odot}$, mass ratio of $\sim 0.5\%$), 2M0103AB is a close binary system composed of 2 late M dwarfs, whose combined mass is $\sim 0.36M_{\odot}$, resulting in a mass ratio of approximately 3.6% for the system.

The position of the companion at each epoch was derived by Moffat-fitting and the orientation of the detector was calibrated using NACO calibration images of theta Ori. obtained close in time of the science images. As shown on table 3, the relative astrometry is accurate enough to detect the orbital motion of the companion around the center of mass of the system, with a projected motion of 77 ± 15 mas over ten years. The corresponding velocity at 47.2 pc is $1.7 \pm 0.3 \text{ km.s}^{-1}$. The Keplerian velocity, assuming a circular orbit of 84 AU around the $0.36M_{\odot}$ system is 1.96 km.s^{-1} , corresponding to a period of 1280 years and is fully compatible with our measurement. It is to be noted that the secondary and the companion rotate in the same direction and that their observed orbital motion can be compatible with a face-on orbit but not with an edge-on one.

3. A challenge for stellar and planetary formation theories

2MASS0103(AB)b has a companion mass to host system mass ratio of ~ 0.036 , which is too low to match known low mass multiple systems (See Fig.3 and also Allers et al., 2007), but still higher than most star-planet systems confirmed so far. Systems with similar mass ratio, but almost

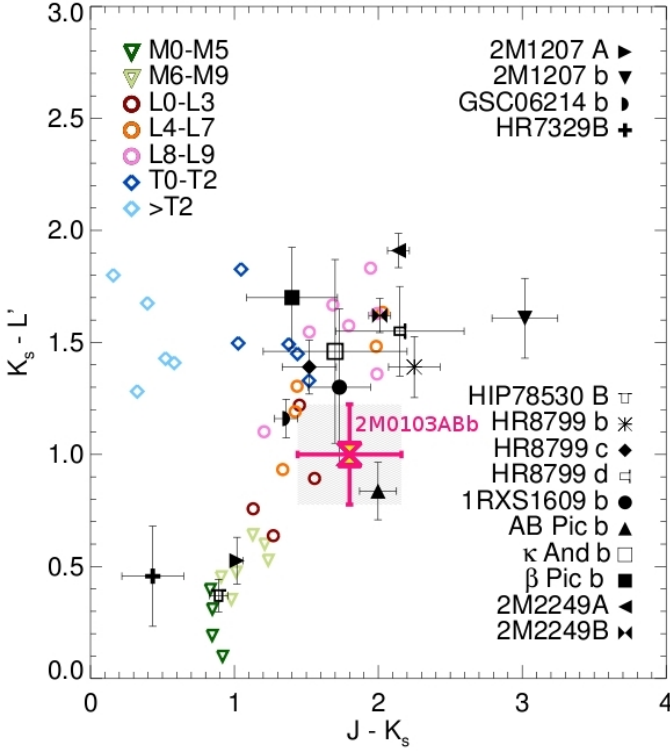


Fig. 2. $J - K_s$ versus $K_s - L$ colour-colour diagram showing 2MASS0103(AB)b together with other known planetary and brown dwarf companions to young stars (taken from Bonnefoy et al. 2013; Bailey et al. 2013). The symbols without error bars show the colour of field M, L and T dwarfs (taken from Golimowski et al. 2004).

Table 4. Companion absolute magnitudes compared with BT-Settl isochrones at 30Myr and 5Gyr (field hypothesis) absolute magnitudes, and other known companions at the planet/brown dwarf mass boundary.

Companions	M_J	M_H	M_{K_s}	$M_{L'}$
2M0103ABb	12.1 ± 0.3	10.9 ± 0.2	10.3 ± 0.2	9.3 ± 0.1
κ And.b	12.7 ± 0.3	11.7 ± 0.2	11.0 ± 0.4	9.5 ± 0.1
ABpic.b	12.9 ± 0.1	11.4 ± 0.1	10.8 ± 0.1	9.9 ± 0.1
Models				
12 M_{Jup}	12.8	11.9	11.3	10.0
15 M_{Jup}	10.9	10.3	9.9	9.0
Field	10.8	10.3	10.0	9.4

one order of magnitude more massive, with 55-95 M_{Jup} brown dwarfs or very low-mass stars orbiting massive (1.2-2 M_{\odot}) stars, have been identified by Janson et al. (2012). In case formation mechanisms would simply scale with mass, the same processes could be at work to explain the formation of these very different kind of objects. If we keep to more similar low-mass star systems shown on Fig. 3, the mass ratio of 2MASS0103(AB)b is very close to those of DH tau B (8-22 M_{Jup} , separation of 330 AU) and CHXR 73b (7-20 M_{Jup} , separation of 210 AU) (Itoh et al. 2005; Luhman et al. 2006), but its projected separation is much smaller. Luhman et al. (2006) state that neither DH tau B nor CHXR 73b could be formed in situ by core-accretion or disc instability because of the very large separation from their host stars, and the same holds for the 1100 AU can-

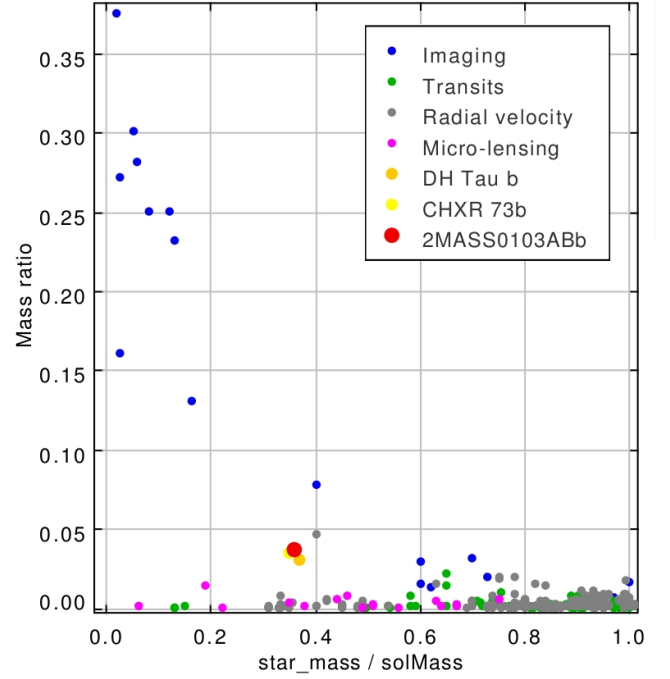


Fig. 3. Substellar companion to stellar host mass ratio versus stellar host mass, sorted by their discovery technic, from the exoplanet.eu database (Schneider et al. 2011).

didate companion to SR12AB (Kuzuhara et al. 2011). The case is different for 2MASS0103(AB)b, at a separation of only 84 AU. At such separations, a formation in a gravitationally unstable primordial circumbinary disk would be fully compatible with planetary formation by gravitational instabilities, as described by Boss (2011). However, this scenario is discussed: Dodson-Robinson et al. (2009) claim that objects formed by disc instabilities around M-dwarfs should have $\sim 10\%$ of the mass of the host system meaning that 2MASS0103(AB)b would not be massive enough for such a scenario, while other studies (Rafikov 2009; Stamatellos et al. 2011) find that such low-mass discs cannot fragment at all. Simultaneous formation and ejection of the 3 components in the massive disc of a more massive original host star is plausible, in a scenario akin to what is described in Stamatellos & Whitworth (2009), but the central binary components, with masses of 0.17 and 0.19 M_{\odot} are more massive than most objects formed in Stamatellos & Whitworth (2009) simulations.

A planetary formation scenario by core-accretion (e.g. Kennedy & Kenyon 2008; Mordasini et al. 2009; Rafikov 2011) can very probably be excluded for several reasons. First, the separation is too large for a formation in situ. Second, the companion has $\sim 3.6\%$ of the mass of its host system, which is of the order of magnitude of the maximum total mass of the protoplanetary disc from which core-accretion planets are formed. Finally, such a 12-14 M_{Jup} companion would be a very rare occurrence, according to the core-accretion planetary mass function derived by Mordasini et al. (2012).

A purely stellar formation mode by turbulent core fragmentation (see e.g. Padoan & Nordlund 2002; Bate 2009; Hennebelle & Chabrier 2011) is plausible, and in this case 2MASS0103(AB)b would be an extreme case of

hierarchical triple stellar with a third component in the 12-14 M_{Jup} mass range. However, a stellar formation scenario would necessitate that cores can naturally fragment into such low mass objects, without requiring any ejection from the the accretion reservoir (such as described in Reipurth & Clarke 2001; Bate & Bonnell 2005), because it would be difficult to starve the accretion of the third component without also stopping accretion on the central binary. From hydrodynamical simulations of stellar formation by cloud fragmentation, Bate (2012) claims that “brown dwarfs with masses $<15 M_{Jup}$ should be very rare”, implying that formation by direct core fragmentation of a 12-14 M_{Jup} object such as 2MASS0103(AB)b would be possible but uncommon.

In any case, the discovery of 2MASS0103(AB)b brings most current stellar and planetary formation theories to their limits while others, such as core-accretion, can probably be excluded. The very existence of such a peculiar system therefore provides a very valuable test case against which current and future stellar and planetary formation theoretical models can be tested.

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